

PERFORMANCE EVALUATION AND MODELING OF EROSION RESISTANT TURBINE ENGINE THERMAL BARRIER COATINGS

Dr. Robert A. Miller, Dr. Dongming Zhu, and Dr. Maria Kuczmarski
NASA Glenn Research Center
Cleveland, Ohio 44135
Abstract

The erosion resistant turbine thermal barrier coating system is critical to the rotorcraft engine performance and durability. The objective of this work was to determine erosion resistance of advanced thermal barrier coating systems under simulated engine erosion and thermal gradient environments, thus validating a new thermal barrier coating turbine blade technology for future rotorcraft applications. A high velocity burner rig based erosion test approach was established and a new series of rare earth oxide- and $\text{TiO}_2/\text{Ta}_2\text{O}_5$ -alloyed, ZrO_2 -based low conductivity thermal barrier coatings were designed and processed. The low conductivity thermal barrier coating systems demonstrated significant improvements in the erosion resistance. A comprehensive model based on accumulated strain damage low cycle fatigue is formulated for blade erosion life prediction. The work is currently aiming at the simulated engine erosion testing of advanced thermal barrier coated turbine blades to establish and validate the coating life prediction models.



Performance Evaluation and Modeling of Erosion Resistant Turbine Engine Thermal Barrier Coatings

Dr. Robert A. Miller, Dr. Dongming Zhu *, Dr. Maria Kuczmarski

**Structures and Materials Division
NASA Glenn Research Center
Cleveland, Ohio**

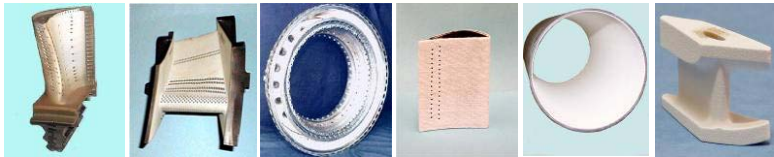
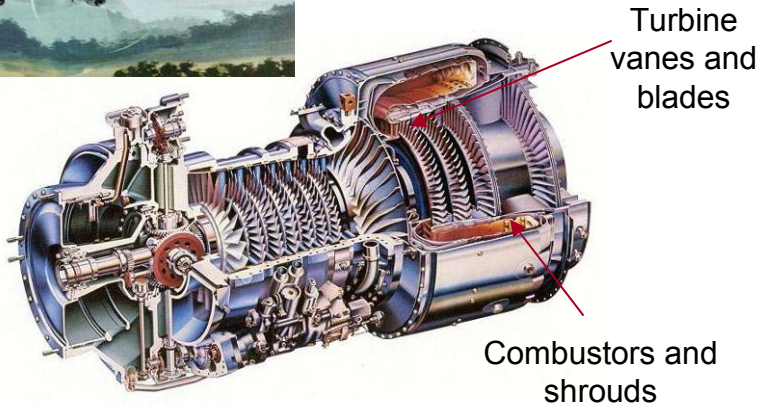
* Army Research Laboratory at NASA Glenn Research Center; Presenter

NASA Fundamental Aeronautics Program Annual Meeting, Atlanta, Georgia,
October 7 - 9, 2008



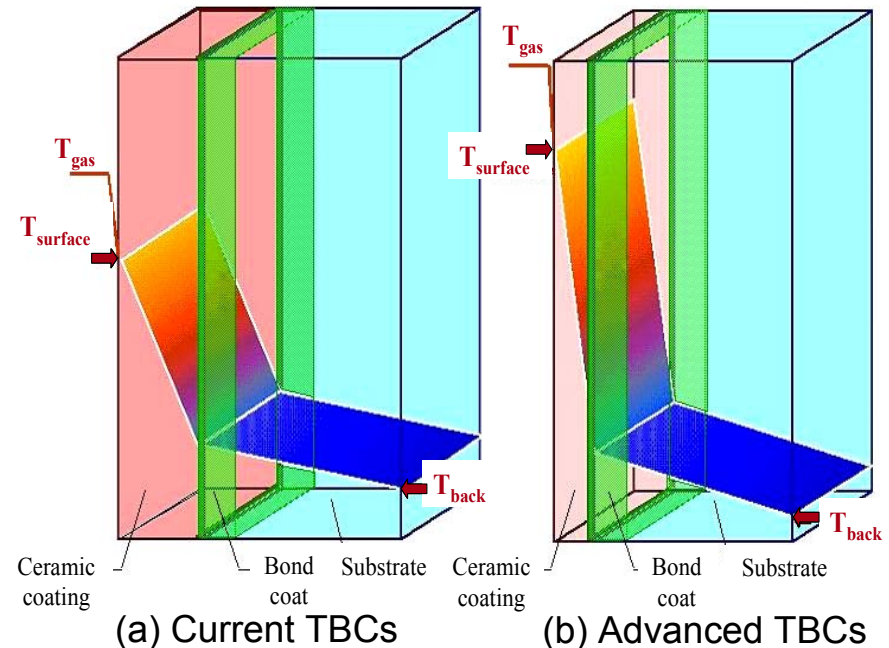
Motivation

- Innovative turbine coating and component materials are enabling technologies for advanced rotorcraft engine development
- Durable thermal barrier coating (TBC) technology is especially crucial for improving rotorcraft engine performance and reliability



Component technologies for reduced engine specific fuel consumption, increased power density, and reduced maintenance cost

Advanced TBCs can significantly increase turbine inlet temperature and thus efficiency





Erosion Resistant Thermal Barrier Coatings for Improved Turbine Blade Life

- **Objective**

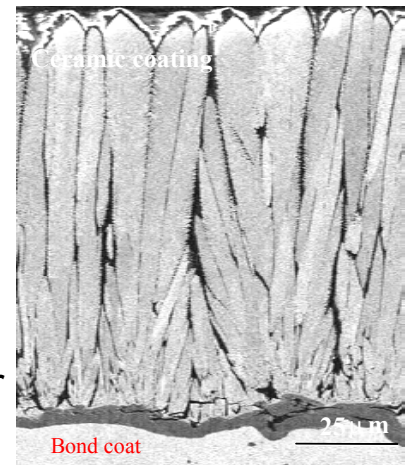
- Develop erosion resistant turbine blade thermal barrier coatings
- Develop physics-based life model and design tools for predicting blade coating erosion and degradation under simulated engine environments

- **Approach**

- Establish advanced erosion high-heat-flux test rigs for turbine TBC evaluations
- Develop advanced thermal barrier coatings based on nano-tetragonal t' phase toughening approaches
- Advanced mechanism- and physics-based modeling

- **Benefits**

- Facilitate turbine thermal barrier coating design and applications
- Improve erosion resistance and durability
- Increase turbine temperature capability by 300 ° F leading to higher fuel efficiency
- Establish advanced modeling methodologies



Typical turbine airfoil thermal barrier coating



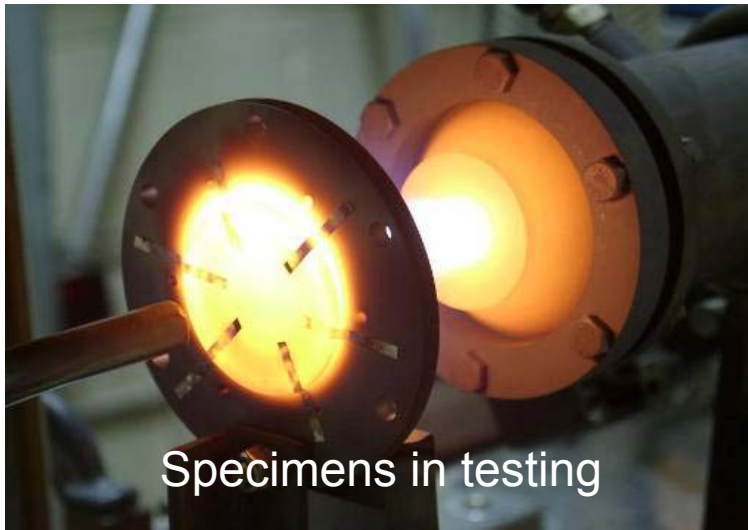
Outline

- **High temperature erosion testing development**
 - High velocity burner erosion rig simulating engine environments
 - Computational Fluid Dynamics (CFD) modeling
 - Experimental validation of high temperature erosion testing
- **Low conductivity turbine thermal barrier coating developments**
 - Low conductivity TBC design approach
 - High toughness erosion resistant turbine airfoil TBC development
 - Calcium-magnesium-alumino-silicate (CMAS) interaction testing
- **Coating Performance and Life Prediction**
 - High toughness turbine erosion coating modeling
 - Sintering-creep, oxidation and thermo-mechanical fatigue mechanisms
- **Future Plans**
- **Summary**



High Velocity Burner Erosion Rig

- Burner capable of up to Mach 1 velocity with erodent particulate injection
- 0.75" to 1" diameter exhaust nozzle
- Temperature up to 2200 ° F
- Thermal gradient erosion testing
- Flexible test configurations
 - 1" and 2" diameter disk specimens
 - Coated turbine blades



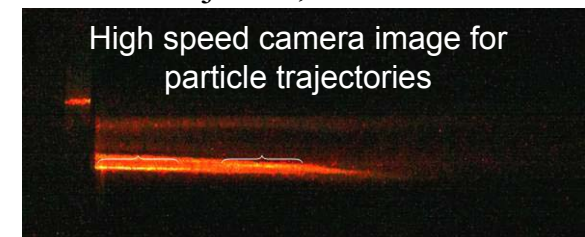
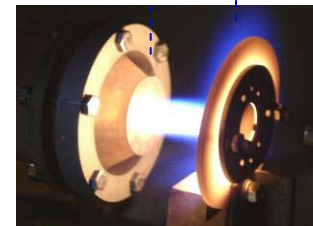
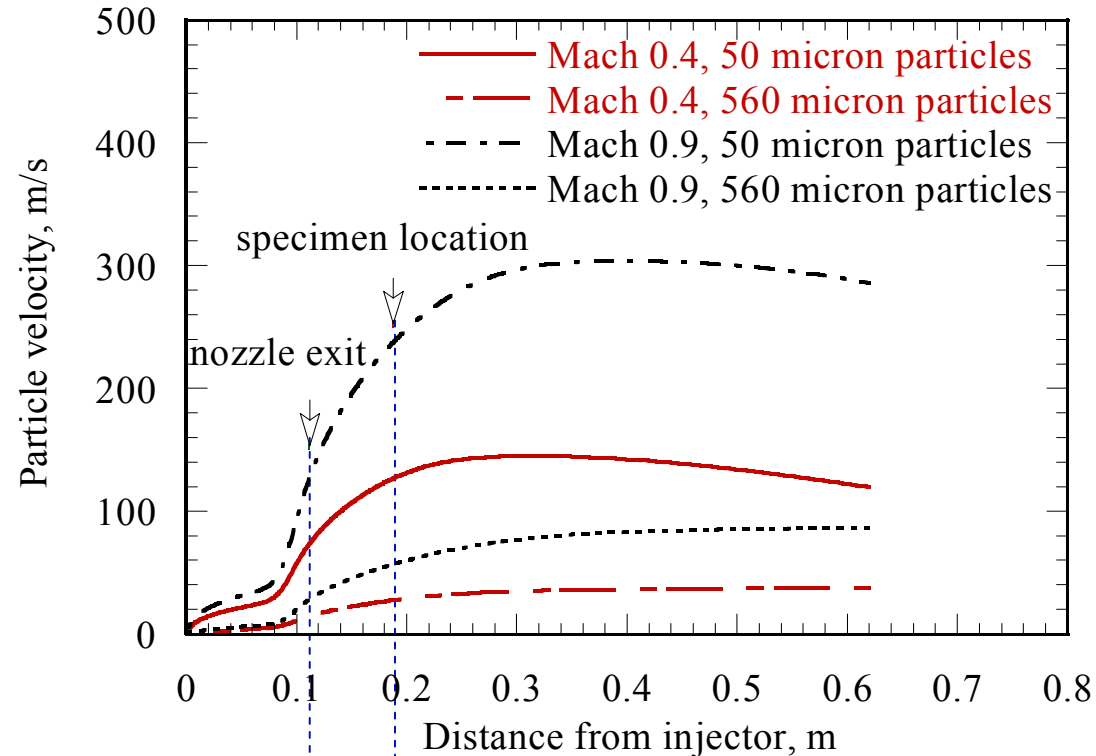
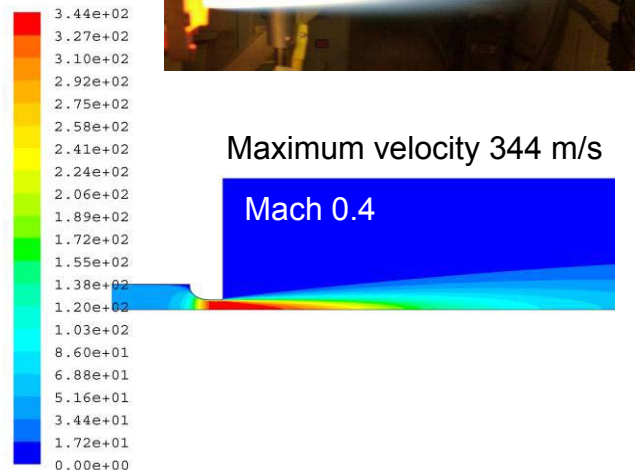
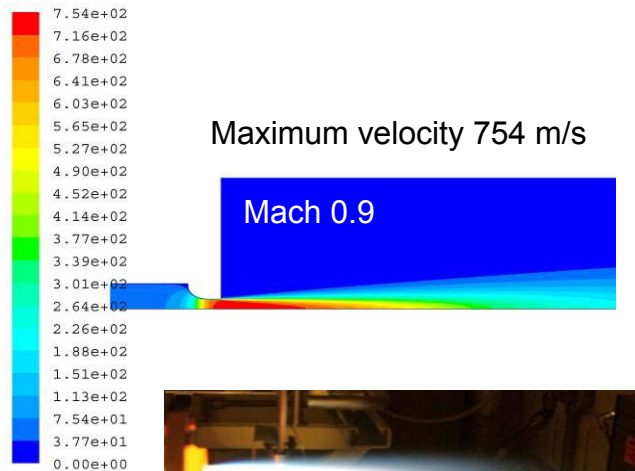
Mach 0.3-1.0 burner erosion rig



Computational Fluid Dynamics (CFD) Modeling

- **Computational Fluid Dynamics (CFD) modeling predicting burner flow and particle velocities in conjunction with experiment validation**

Gas velocity m/s

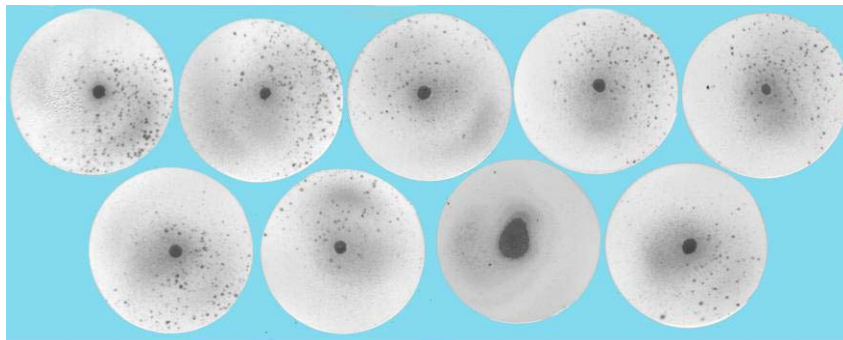
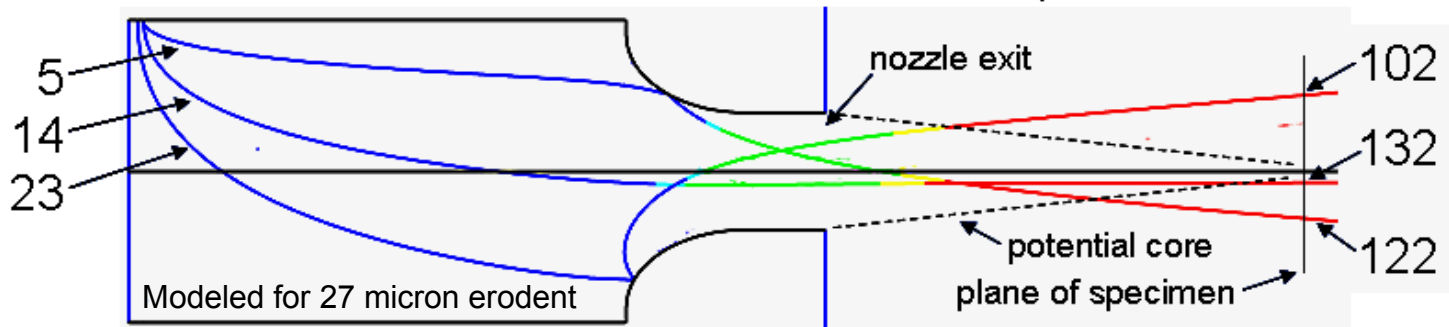




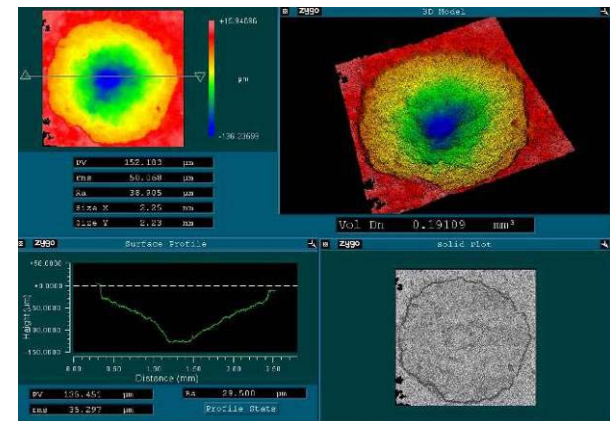
Modeling of Erodent Particle Trajectories and Coating Erosion Test Approach

- Erosion particulate trajectories modeled to understand high temperature erosion test configuration
- The test rig demonstrated in coating erosion screening tests

Injection velocity m/sec :



- Examples of eroded 1" diameter disk specimens
- Erosion crater profiles similar to those in erosion standard G76-05 for coating downselect

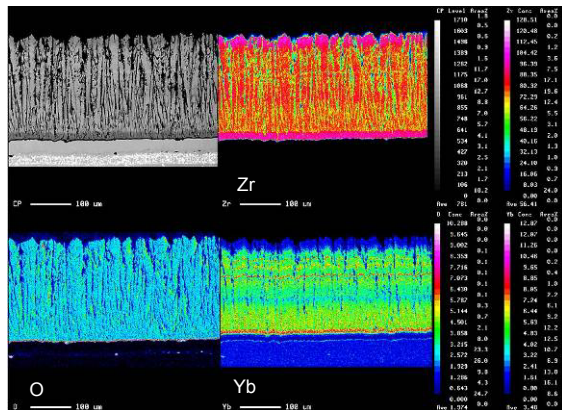


An erosion crater profile after testing

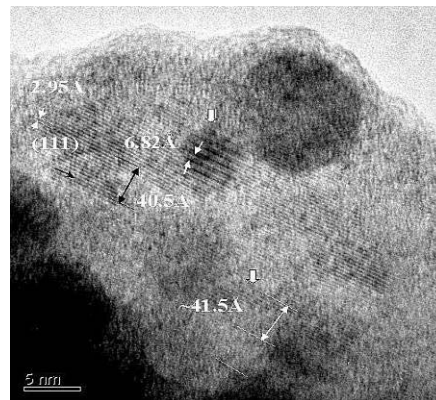


Erosion Resistant Low Conductivity Thermal Barrier Coatings

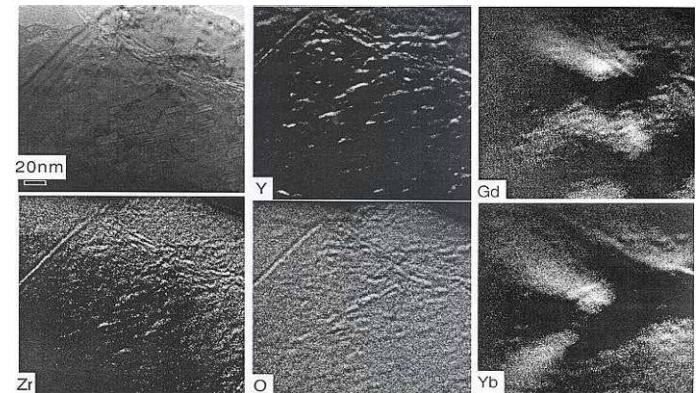
- **Multi-component oxide defect clustering approach** (Zhu and Miller, *US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US patent application 11/510,574*)
 e.g.: $\text{ZrO}_2\text{-Y}_2\text{O}_3\text{-Nd}_2\text{O}_3(\text{Gd}_2\text{O}_3, \text{Sm}_2\text{O}_3)\text{-Yb}_2\text{O}_3(\text{Sc}_2\text{O}_3) - \text{TiO}_2\text{-Ta}_2\text{O}_5$ systems
 ↪ Primary stabilizer ↪ Oxide cluster dopants with distinctive ionic sizes ↪ Toughening dopants
- **Lower thermal conductivity and improved thermal stability**



Advanced turbine WDS composition maps



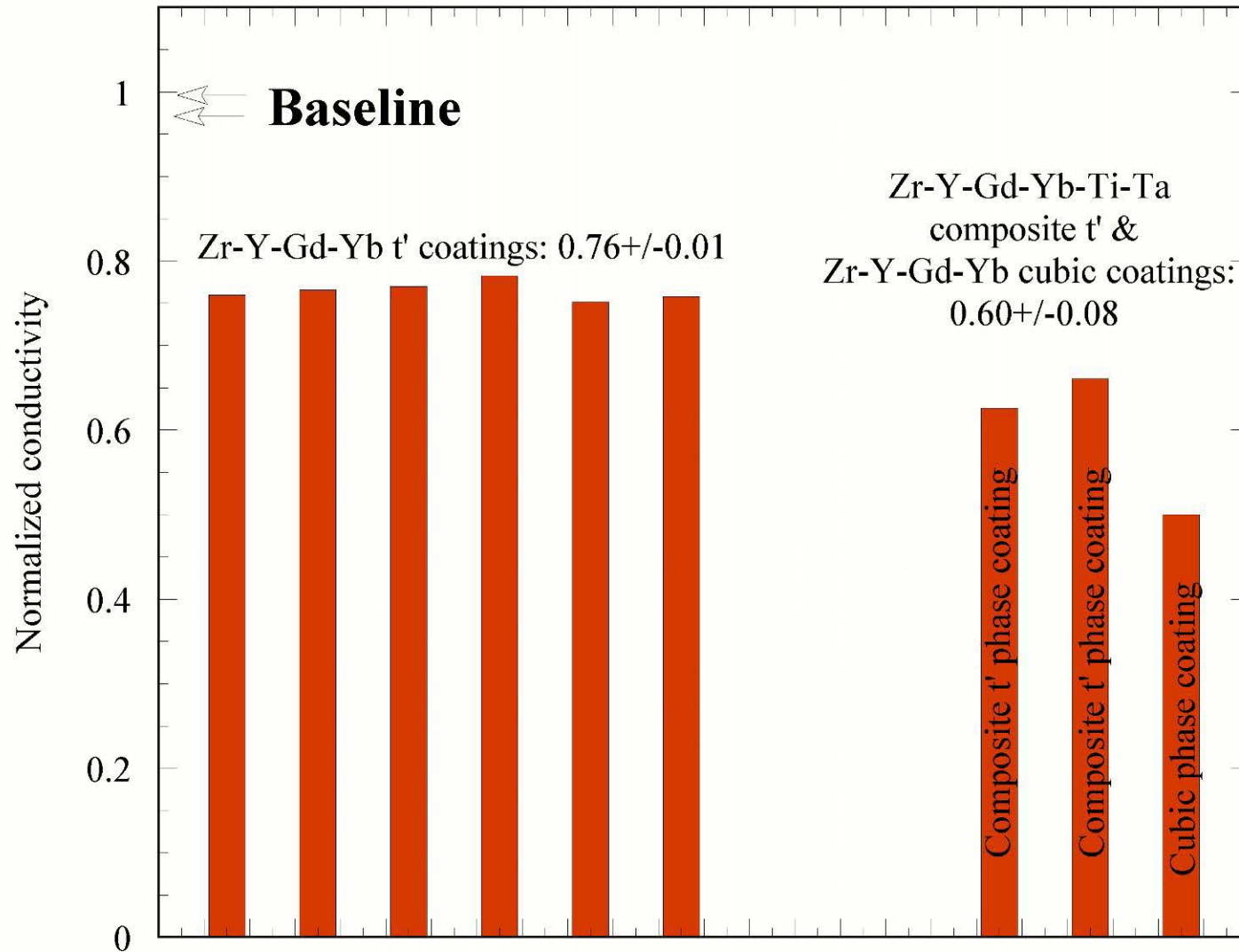
TEM Moiré fringes of EB-PVD $\text{ZrO}_2\text{-(Y, Nd, Yb)}_2\text{O}_3$



EELS elemental maps of EB-PVD $\text{ZrO}_2\text{-(Y, Gd, Yb)}_2\text{O}_3$



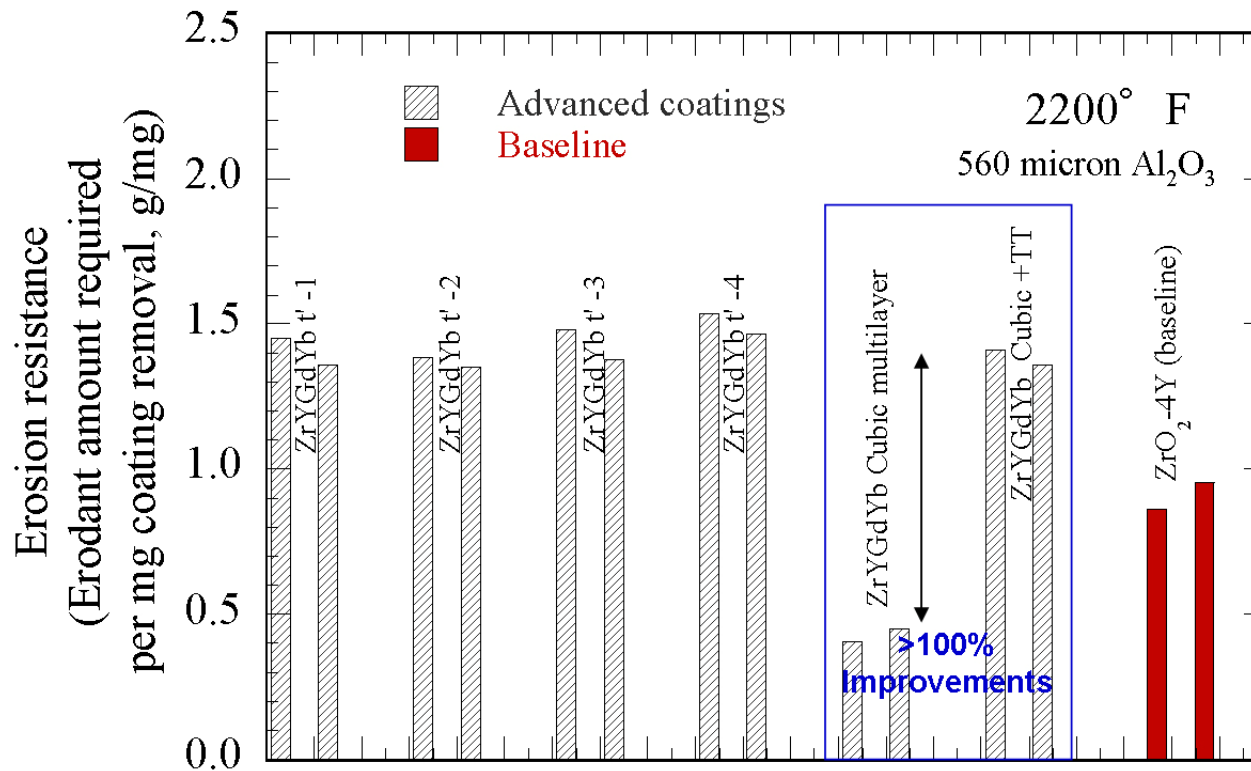
Thermal Conductivity of Advanced Turbine Thermal Barrier Coatings





Impact Resistant Low Conductivity Thermal Barrier Coatings

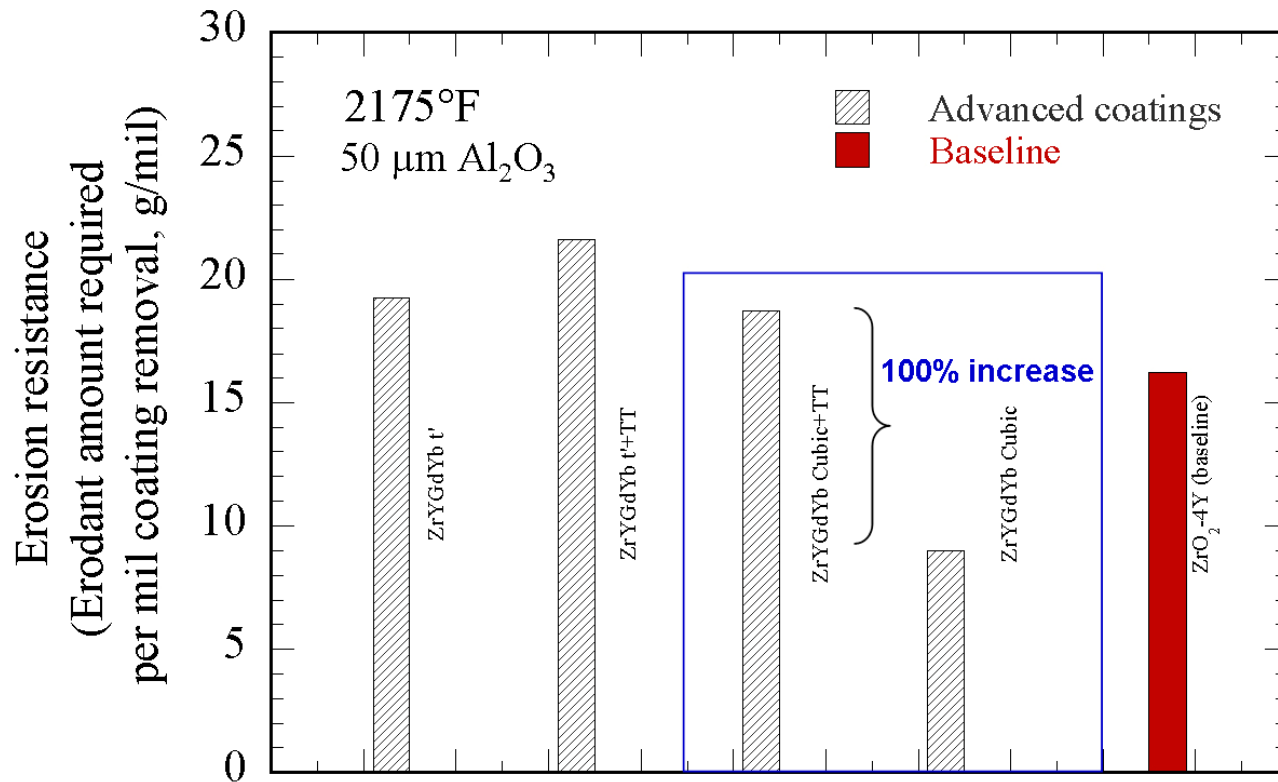
- Tetragonal t' phase toughened low conductivity coatings showed improved impact resistance compared to the cubic-phase coatings in impact tests





Erosion Resistance of Low Conductivity Thermal Barrier Coatings

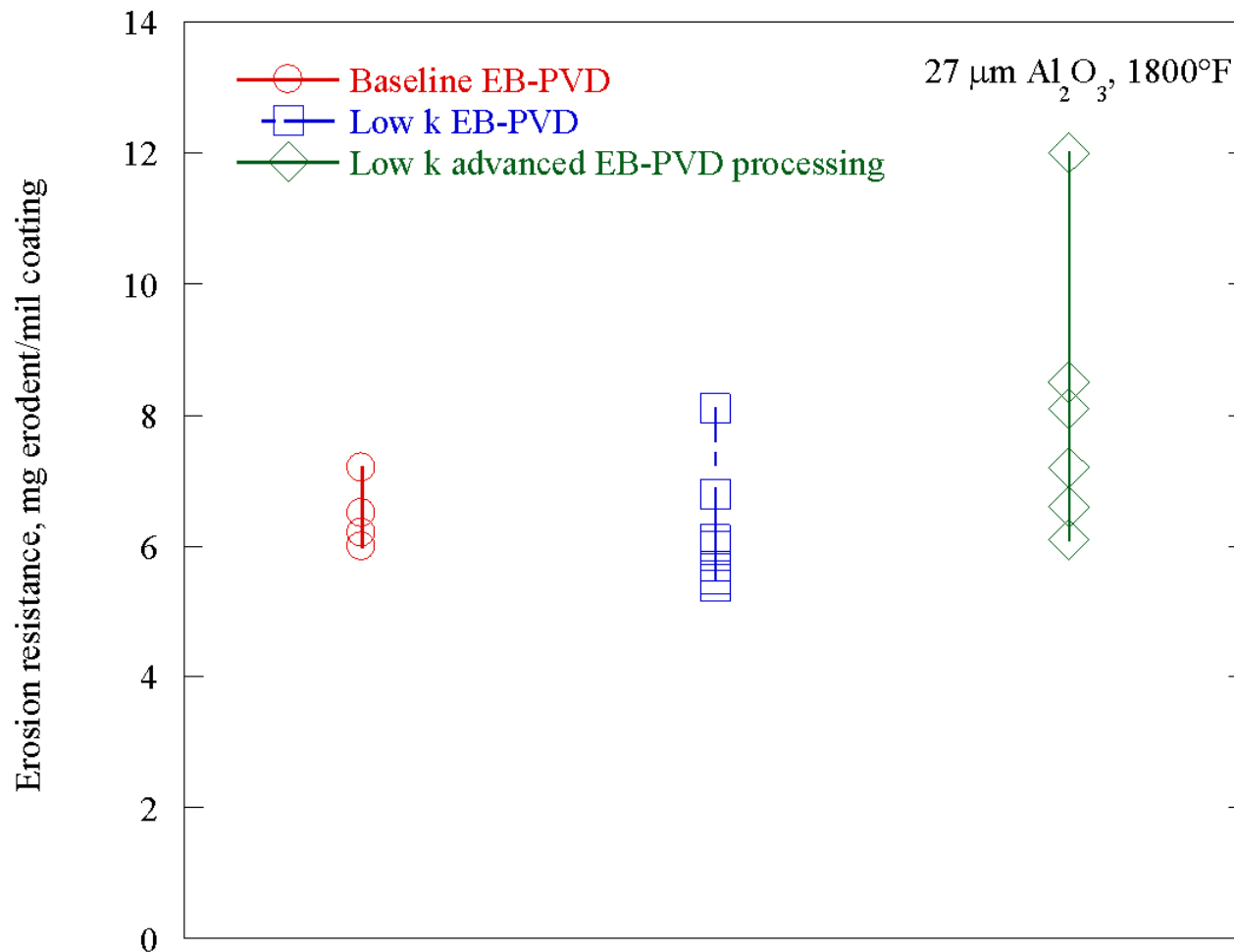
- Tetragonal t' phase toughened low conductivity coatings showed improved 50 micron size particulate erosion resistance compared to the cubic-phase coatings in erosion tests





Erosion Resistance of Low Conductivity Thermal Barrier Coatings

- **Advanced processing showed promise in improving 27 micron particle erosion resistance of low conductivity TBCs**





Physics-Based Erosion Model Development

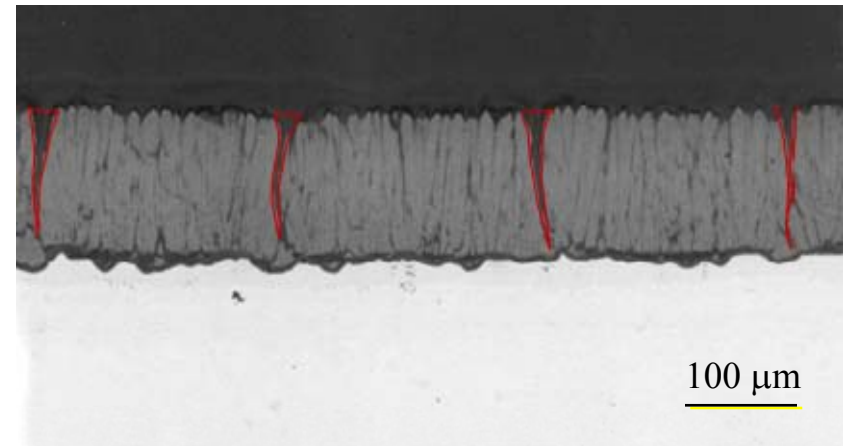
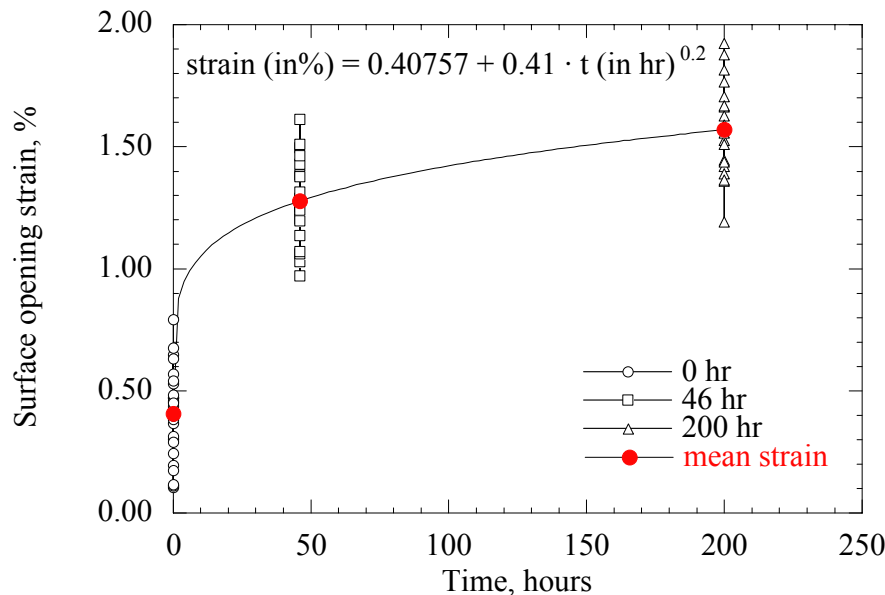
- **Physics-based erosion models being developed to predict turbine TBC erosion and degradation behavior**
- **Multiple physics-base processes and mechanisms considered**
 - Turbine TBC sintering and creep
 - Erosion (erosion fatigue mechanism)
 - Low cycle fatigue
 - Molten Calcium Magnesium Alumino-Silicate (CMAS) interactions

Variable erosion rates during the erosion process under high-heat-flux and thermal gradient cyclic conditions



Sintering Cracks and Delaminations of Thermal Barrier Coatings

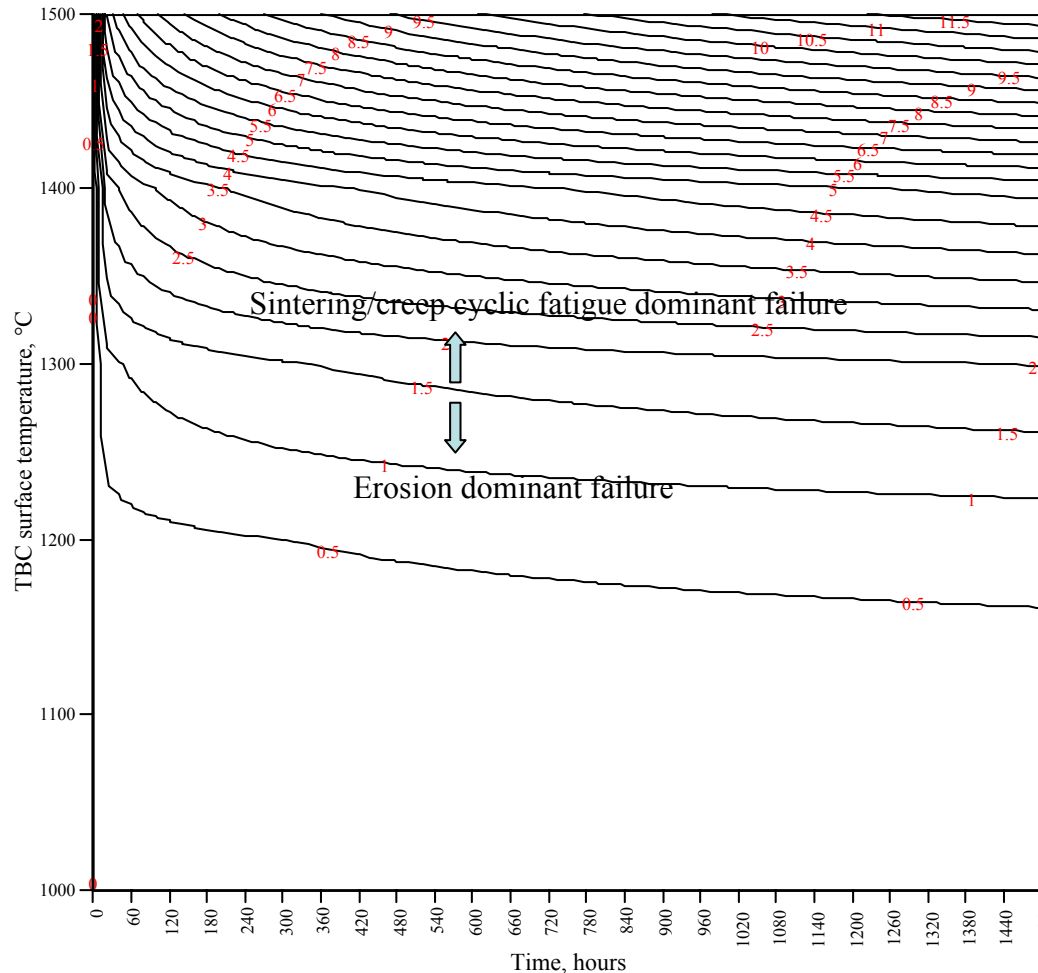
- Baseline ZrO_2 -7wt% Y_2O_3 turbine coating tested under laser simulated engine heat flux conditions
- Sintering strain corresponding to the thermal gradient across the coating ($T_{\text{surface}}=1280^\circ\text{C}$, $T_{\text{interface}}=1095^\circ\text{C}$)
- Coating delamination under high-heat-flux cyclic environments





Modeled Sintering-Creep Strains as a Function of Temperature and Time

- Erosion dominant region vs. sintering-creep dominant region
- Strong interactions in accelerated damage accumulation

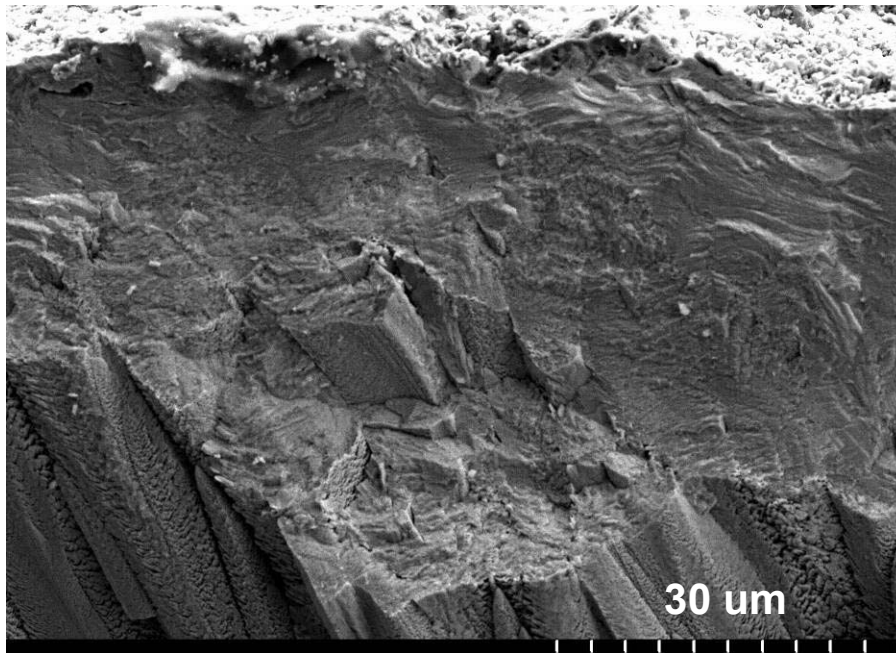




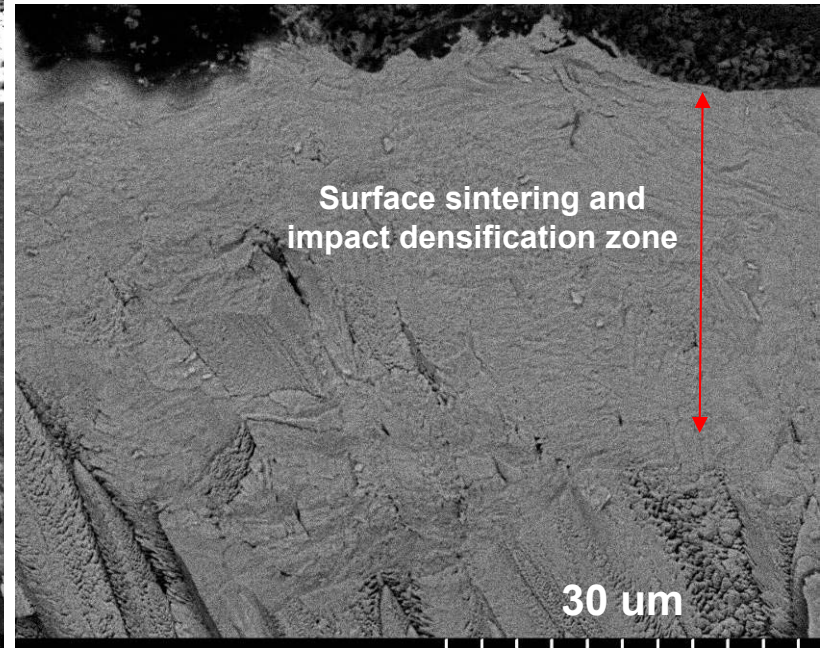
Impact Failure of Advanced Multi-Component Low Conductivity Thermal Barrier Coatings

- Surface sintering and impact densification zone interaction, with subsequent spallation

SEM micrographs of advanced thermal barrier coating after impact/erosion damage



Secondary electron image

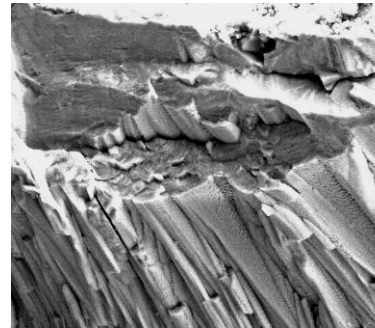


Backscattered electron image



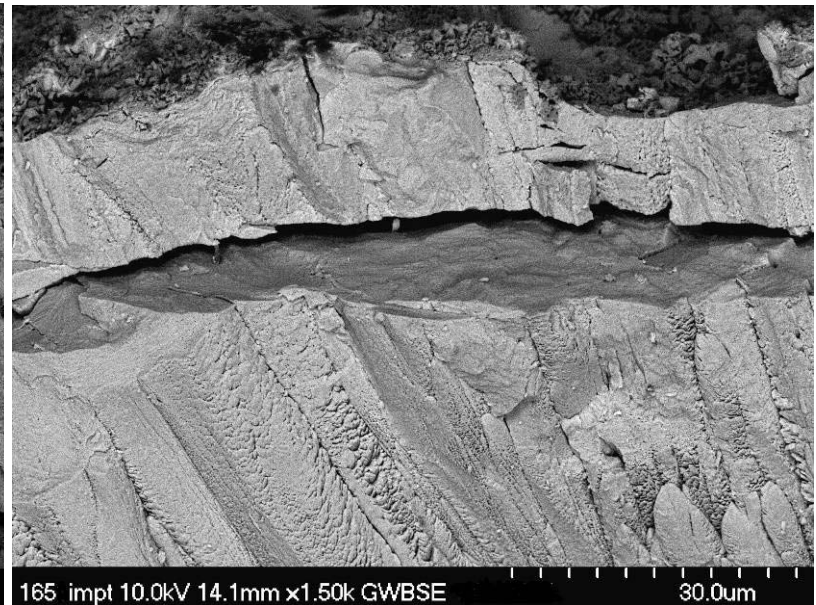
Erosion Damage Accumulations

- Multi-level delaminations under combined erosion impact loading and thermal gradients



165 impt 10.0kV 14.4mm x1.50k GVBSE

30.0um



165 impt 10.0kV 14.1mm x1.50k GVBSE

30.0um



Erosion Rates

— Fatigue strain based models incorporate multiple mechanisms

$$\Sigma(\Delta\varepsilon_{p-erosion}, \Delta\varepsilon_{p-creep}, \Delta\varepsilon_{p-heat_flux}, \Delta\varepsilon_{p-LCF}, \Delta\varepsilon_{p-oxidation}) \cdot N_f^{1/2} = \varepsilon_c$$

Erosion rate (mg/g erodent) in erosion dominant regime – dynamic impact effect will be incorporated

$$\Delta\varepsilon_{p-erosion} \cdot N_f^{1/2} = \varepsilon_c$$

$$e_{TBC} = K \cdot \frac{\rho_{TBC} \cdot \rho_{erodent}^{1/2} \cdot v^3}{\varepsilon_c^2 \cdot H^{3/2}}$$

- K - Constant
- $\rho_{TBC}, \rho_{erodent}$ - Densities of coating and erodent, respectively
- ε_c - Critical strain to failure
- H - Dynamic hardness



The erosion model development and validation:
Emphasizing more realistic testing condition
and mechanisms interactions



Additional Failure Driving Forces

- Fatigue strain based models incorporate multiple mechanisms
- Elastic modulus and activation energies determined from experiments

- High heat-flux effect

$$G = \frac{1}{6} \left(\frac{1 + \nu_1}{1 - \nu_1} \right) E_1 h (\alpha_1 (T_s - T_0))^2$$

- Thermal expansion mismatch

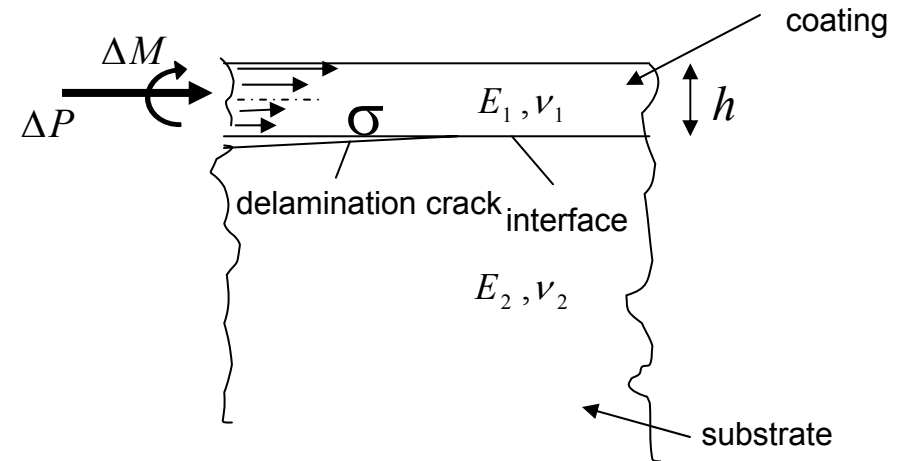
$$G = \sigma^2 h / 2 \bar{E}$$

$$= [Eh(1 + \nu) / (1 - \nu)] (\Delta \alpha \Delta T)^2 / 2$$

- Creep and oxidation

$$\dot{\epsilon}_p = A \cdot \exp \left(- \frac{Q_{volume} + Q_s}{RT} \right) \cdot \sigma(x) \cdot t^{-s}$$

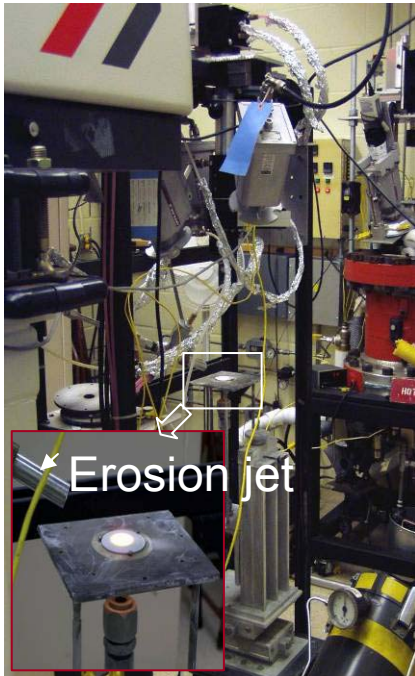
$$\dot{\epsilon}_{p-ox} = B \cdot \exp \left(- \frac{Q_{Volume-ox} + Q_{GB-ox}}{RT} \right)$$





Laser High Heat Flux Rig for Molten Sand Erosion and CMAS Interactions

- CMAS effect taken into account for coating development
- Accelerated failure observed with CMAS interactions
- Modeling emphasis on coating densification and resulting delamination failure



Specimen under the rig test



(a) Upon initial heating

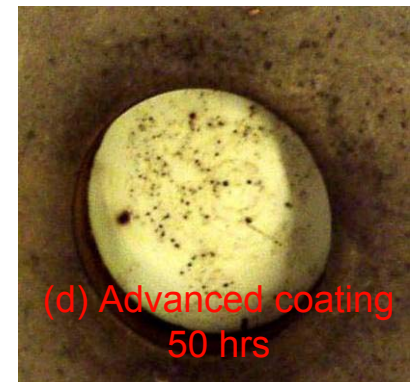


(b) After testing

Combustor TBC



(c) Baseline coating



(d) Advanced coating 50 hrs

Turbine TBCs



Plans

- **Emphasize burner erosion resistance and coating life models**
 - **Optimize high toughness erosion resistant turbine coatings**
 - **Investigate and model erosion, creep, fatigue, and CMAS interactions**
 - **Develop methodologies and key experiments for model validation**
 - **Develop turbine blade TBC erosion-oriented life prediction models and design tools**



Summary

- **High temperature erosion testing capability developed under the Subsonic Rotary Wing project**
- **CFD models established to understand gas and erodent flows**
- **Advanced turbine thermal barrier coatings developed for rotorcraft engines with combined low conductivity and high toughness**
- **Models formulated addressing the erosion, sintering and fatigue interactions – strain damage accumulations**
- **Physics-based turbine blade coating erosion lifing models and model validation emphasized in the current efforts**